Digital Image Processing

Instructor: **Xiaoli Zhao**

- Objectives: This 3-credit course provides education and training to equip students to:
  - *Explain* various image representations, human visual perception, color space, and standards.
  - *Write* computer programs to perform image filtering, enhancement, restoration, and transform.
  - *Perform* various image compression and segmentation using various techniques.
  - *Implement* algorithms to solve real-world image processing and analysis problems.

Text Book and Prerequisites

- **Text book:**
  - Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing, 4rd Ed. Pearson, 2020
  - Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing, 3rd Ed. Pearson, 2007.
- Prerequisites by Topic:
  - Discrete Time Signal Analysis, familiarity with PYTHON

Course Contents

- **Lecture 1:** Image Representations, Visual Perception, Color Space (6 hours)
- **Lecture 2:** Spatial Domain Image Enhancement (10 hours)
- **Lecture 3:** Spatial Domain Image Filtering (10 hours)
- **Lecture 4:** Frequency Domain Image Filtering and Enhancement (10 hours)
- **Lecture 5:** Edge Detection and Segmentation (6 hours)
- **Lecture 6:** Mathematical Morphology (4 hours)

- **Final Exam & Review:** (2 hours)

Grading

- Attendance and Special Performance: 20%

- Presentation, HWs and Processing Labs: 40%

- Final Exam.: 40%

- Special bonus to students with active class participation and biggest exam improvement

1. Digital Image Representations

- Chapter 1 (Introduction)
- Chapter 2 (2.1-2.3 Visual Perception)
- Section 2.4 (Sampling and Quantization)
- Section 6.2 (Color Models & Image Formats)

Elements of Image/Video Processing
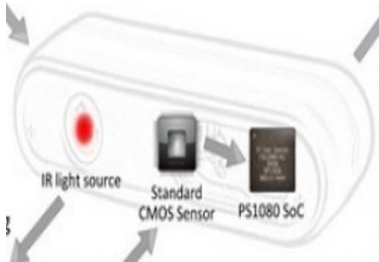
- **Applications:** multimedia, medical, surveillance, TV, video conferencing, video-on-demand,…

- **Acquisition:** sensing and digitizing (film, CCD, digital still camera, video camera, camcorder, Kinect)

- **Storage:** disks, tapes, …

- **Processing:** software on general-purpose or dedicated computers, hardware boards, …

- **Communication:** wireless, Internet, …

- **Display:** TV monitors

Optical Representation of Eye Viewing

Point C is the optical center of the lens

15 m

2.55mm

100 m

17 mm
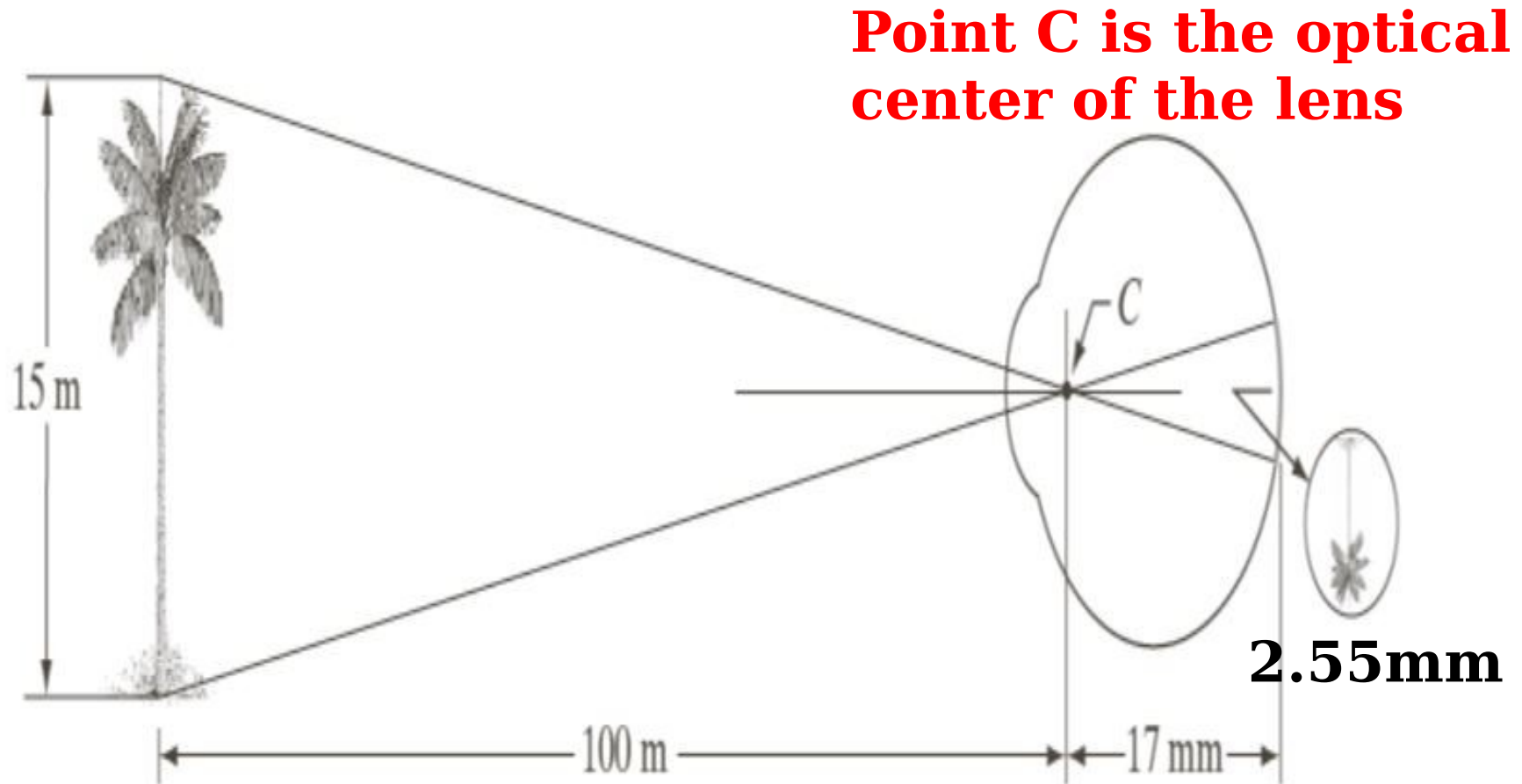
Structure of Human Eyes

- 3 membranes: **Cornea** & **Sclera** (outer cover), **Choroid** (ciliary body & iris), and **Retina**

- Light receptors over retina: cones (6-7 million) & rods (75-150 million)

- **Cones**: located primarily in the central portion of Retina called Fovea, highly sensitive to color, can resolve fine details

- **Rods** give an overall picture of field of view, not involved in color vision, sensitive to
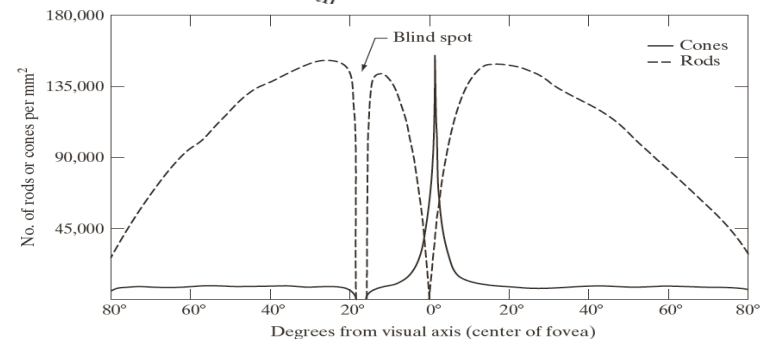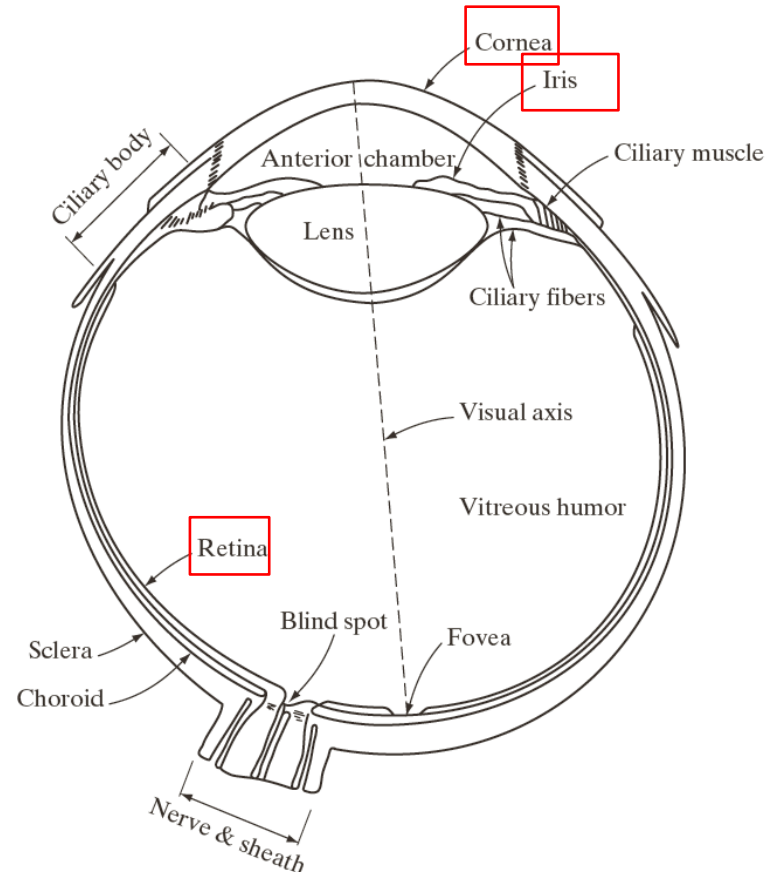
Eyes and Colors

- Rods (~   ) detect movement, shape, and textures (**scotopic vision, dim-light vision**), but unable to convey details because they are connected in bunches.

- Cones (6.5 x   ), only operate in medium to high

   levels of illumination, find details of colors and shades (**photopic vision, bright-light vision**).

- **Thomas Young** (1802): three types of cones each of which is sensitive to a

Absorption of Light in Cones
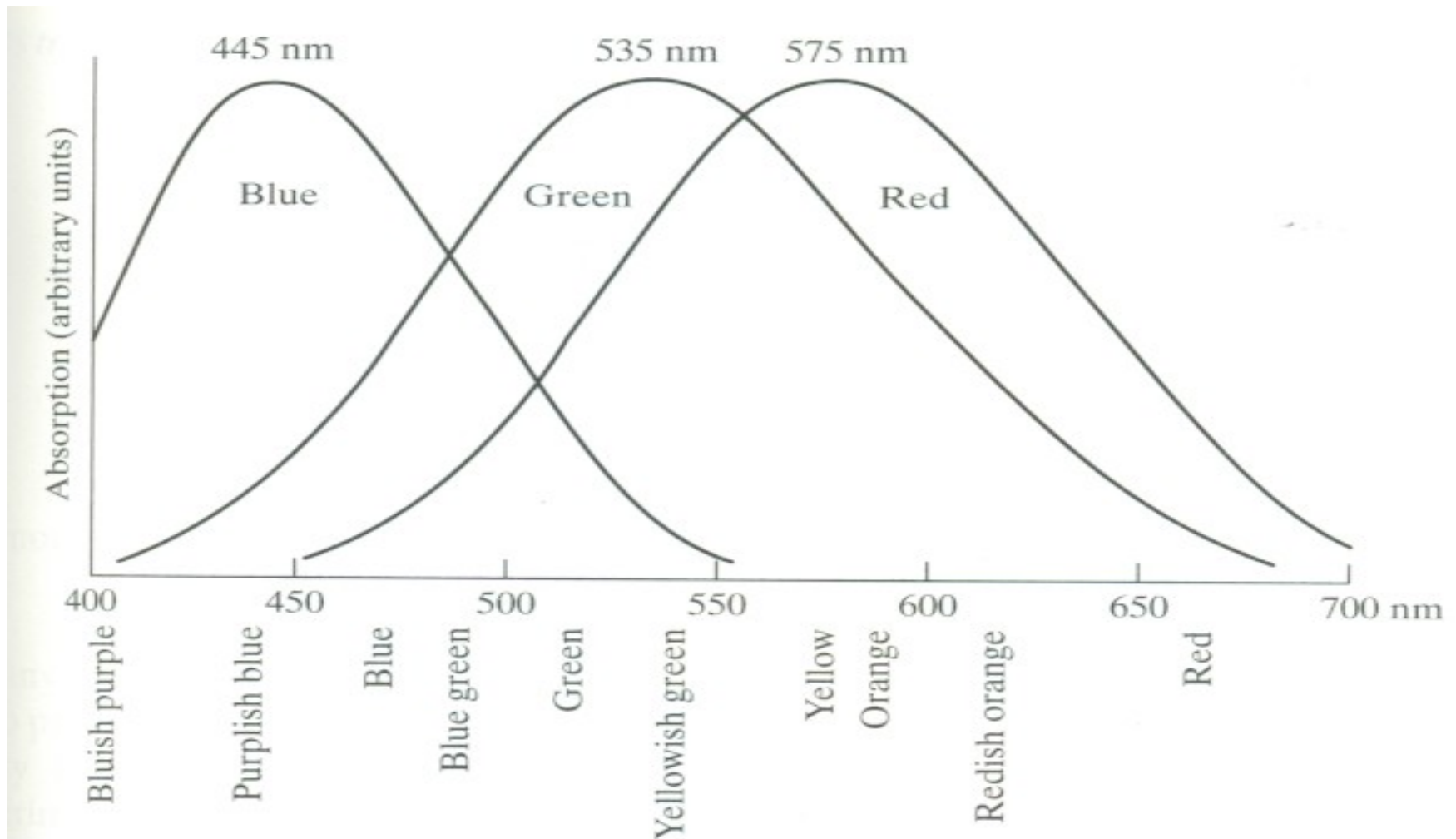
Color Fundamentals

- Chromatic light spans EM spectrum from 380 nm to 770 nm, (more sensitive to green light, then red, then blue).

- **Three basic quantities** of chromatic light: radiance, luminance, and brightness.
  - **Radiance** (watts): total energy flow from the light source.
  - **Luminance** (lumens): amount of energy an observer perceives.
  - **Brightness**: subjective descriptor

A Simplified Human Visual Perception

- The perceived intensity *f(x,y)* consists of light reflected from objects:

  $f(x,y) = I(x,y) \, r(x,y)$

  - $0 < f(x,y) <$ infinity,
  - $0 < I(x,y)$ (illumination) $<$ infinity
  - $0 < r(x,y)$ (reflectance) < 1
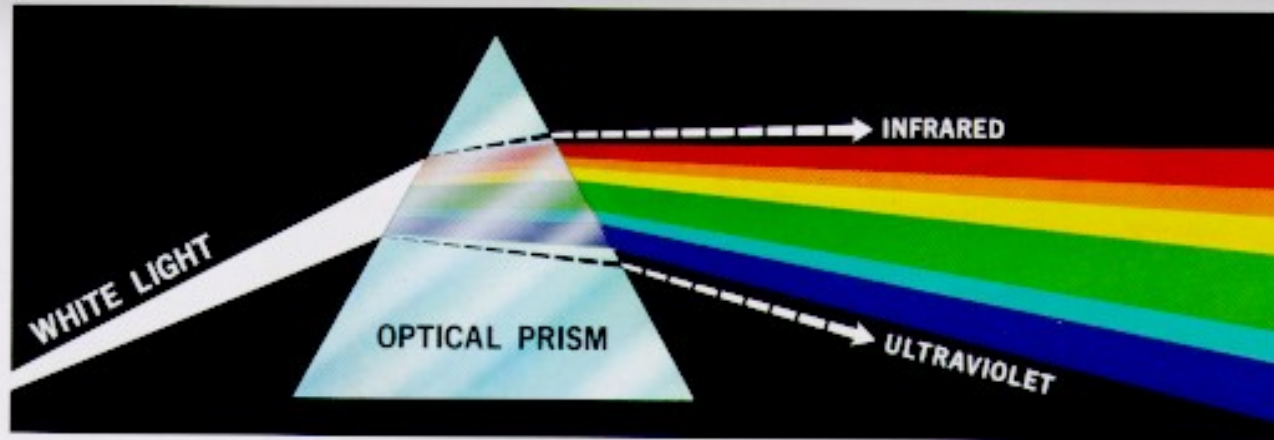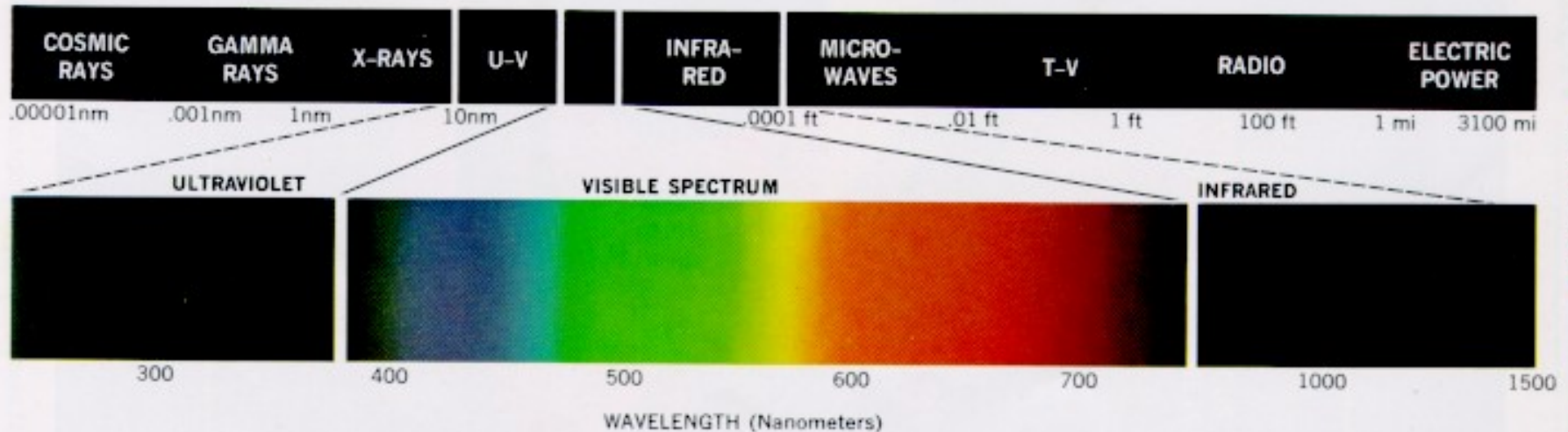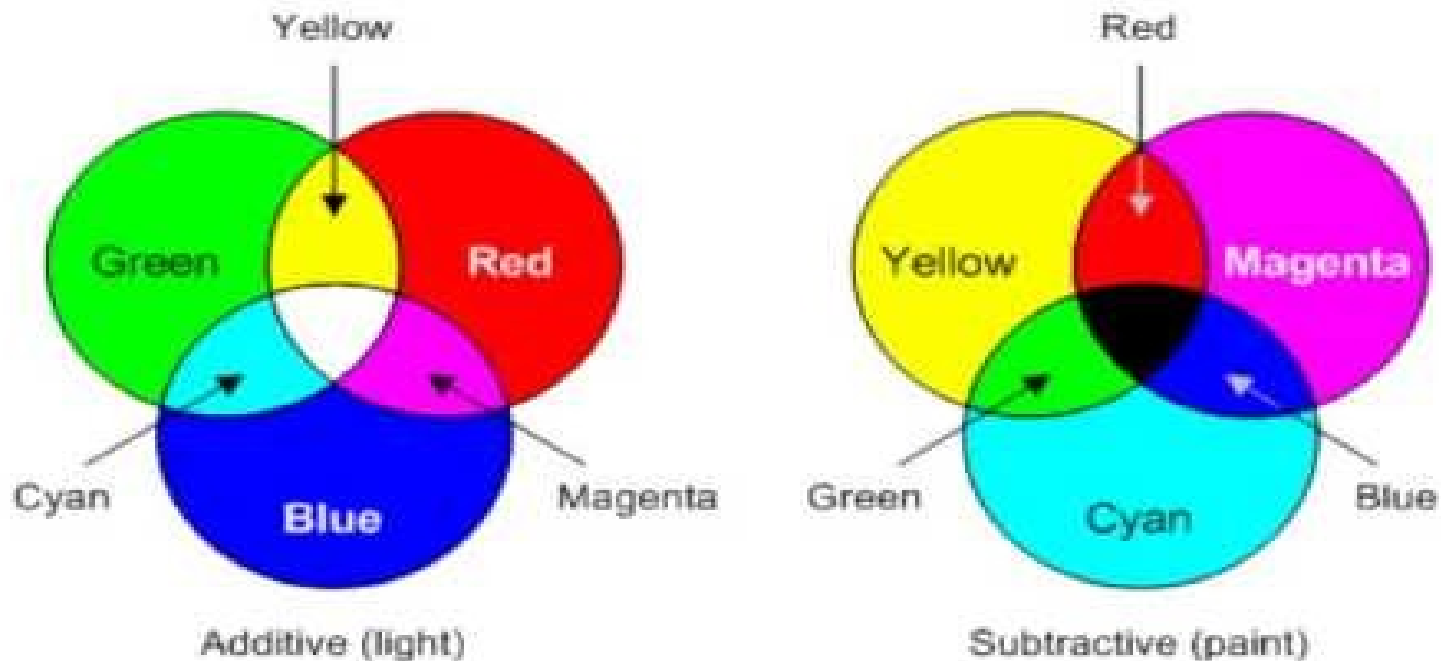
Color Spectrum

Plate I. Color spectrum seen by passing white light through a prism. (Courtesy of General Electric Co., Lamp Business Division.)

Light and Pigments

Additive and subtractive color combinations

Primary & Secondary Colors of Light

Primary & Secondary Colors of Pigments

Primary Colors of Light

- Owing to the structure of the human eye, all colors are seen as various combinations of the three so-called **primary colors**: Red (R), Green (G), and Blue (B). A proper combination of these three primaries produces **white** color.

- **Commission Internationale de l'Eclairage** (CIE) -- International Commission on Illumination adopted three primary colors: R=700 nm, G=546.1 nm, B=435.8 nm.

- **Secondary colors of light:** Magenta (red plus blue), Cyan (green plus blue), and Yellow (red plus green). A proper

Primary Colors of Pigments

- Primary Colors of Pigments (Colorants): Cyan (G-B), Magenta (R-B), Yellow (R-G). They are also called "subtractive primaries". A proper combination of these three primaries produces **black** color.

- A subtractive system used by printers for the rendering of colors with ink.

- By depositing three color pigments on white papers (such as ink-jet printers), each absorbs its complementary light color, i.e., cyan absorbs red, magenta absorbs green, and yellow absorbs blue. By increasing yellow ink, the blue decreases.

- The secondary colors of pigments are red,

16

Additive & Subtractive Color Systems

- **Additive:** colors are created by adding colors to black to create new colors. The more added, the closer to white.
- Additive color environments are self-luminous.

- **Subtractive:** primary colors are subtracted from white to create new colors, the more taken away, the closer to black.
- Any color image reproduced on paper is an example of subtractive color system.

RGB Color System

- The most widely used system (additive). Each pixel is represented as a **triplet,** e.g., Red (255,0,0), Yellow (255,255,0), Green (0,255,0), Cyan (0,255,255), Blue (0,0,255), Magenta (255,0,255).

- (0,0,0) denotes black, and (255,255,255) denotes white. (63,63,63), (127,127,127), etc, represent different shades of **gray.**

RGB 24-Bit Color Cube

FIGURE 6.8 RGB 24-bit color cube.
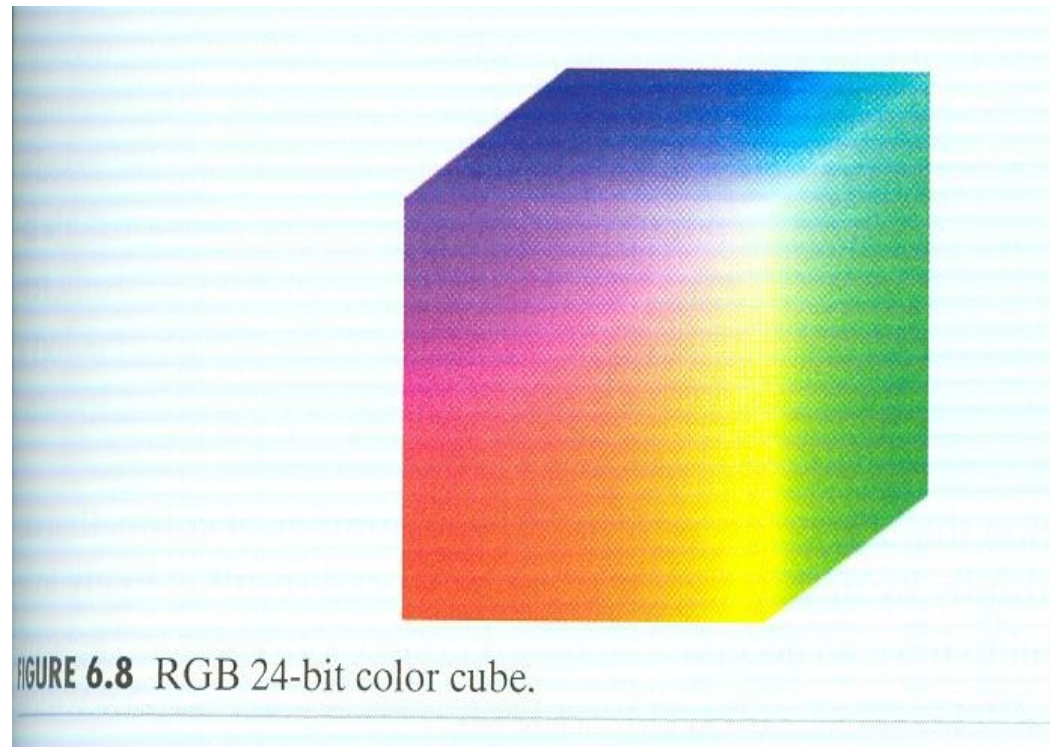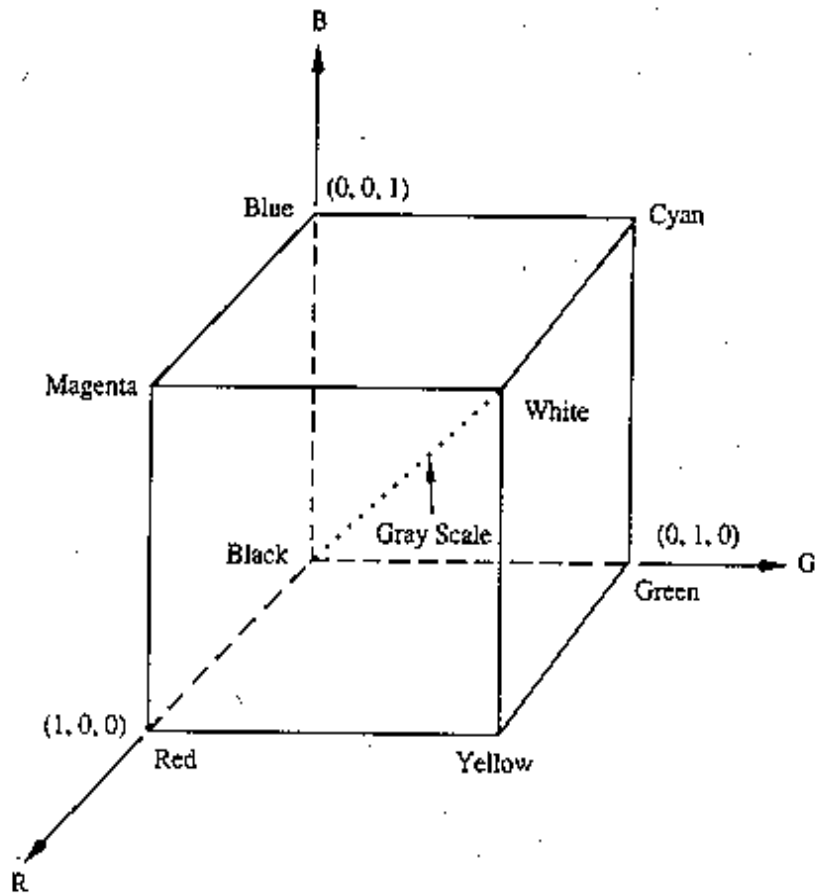
Digitization of Signals

- Sampling: from continuous time to discrete time
- Quantization: from continuous valued to discrete valued

x(t)

(a)

x(n)

3-bit output code

(b)

A Color Photo

f(x,y)
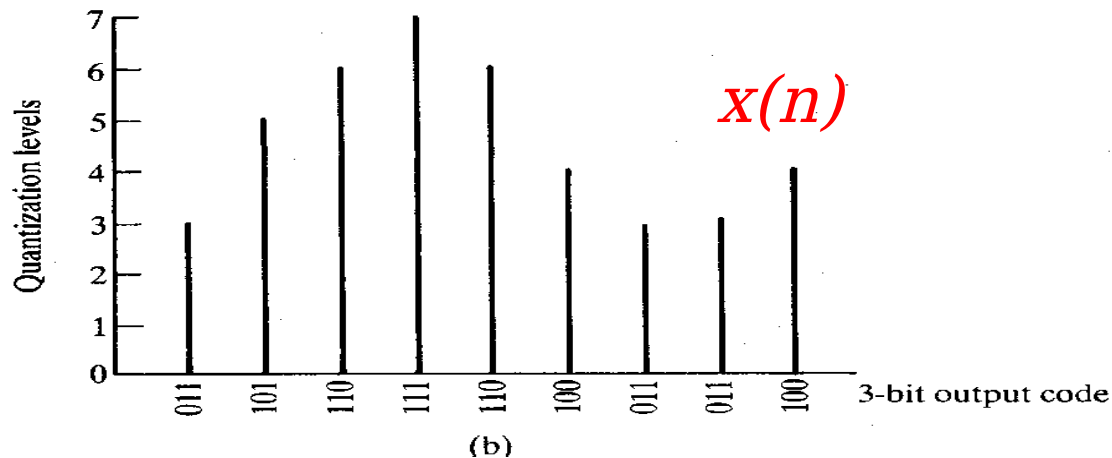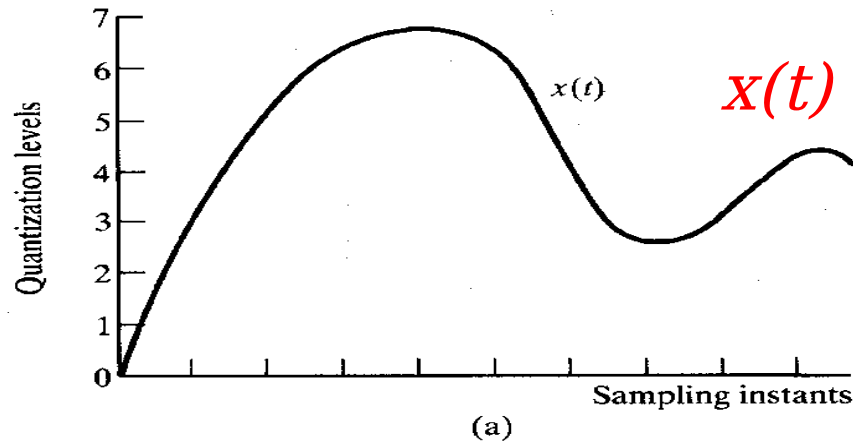
- f(x, y): (x, y) denote the spatial coordinates. In a "digital image", (x,y) is a discrete picture element (**pixel or pel).** For a gray-scale image, f() at any point (x,y) is the brightness (or gray-level) of the image. For color images, each pixel contains 3 numbers representing 3 color components

2-D Sampling (Spatial Domain)

Digital Image Representation

Origin

```
       0   1   2   3 · · ·              · · · N − 1
    0                                              y
    1
    2
    3
    .
    .
    .
```

M − 1
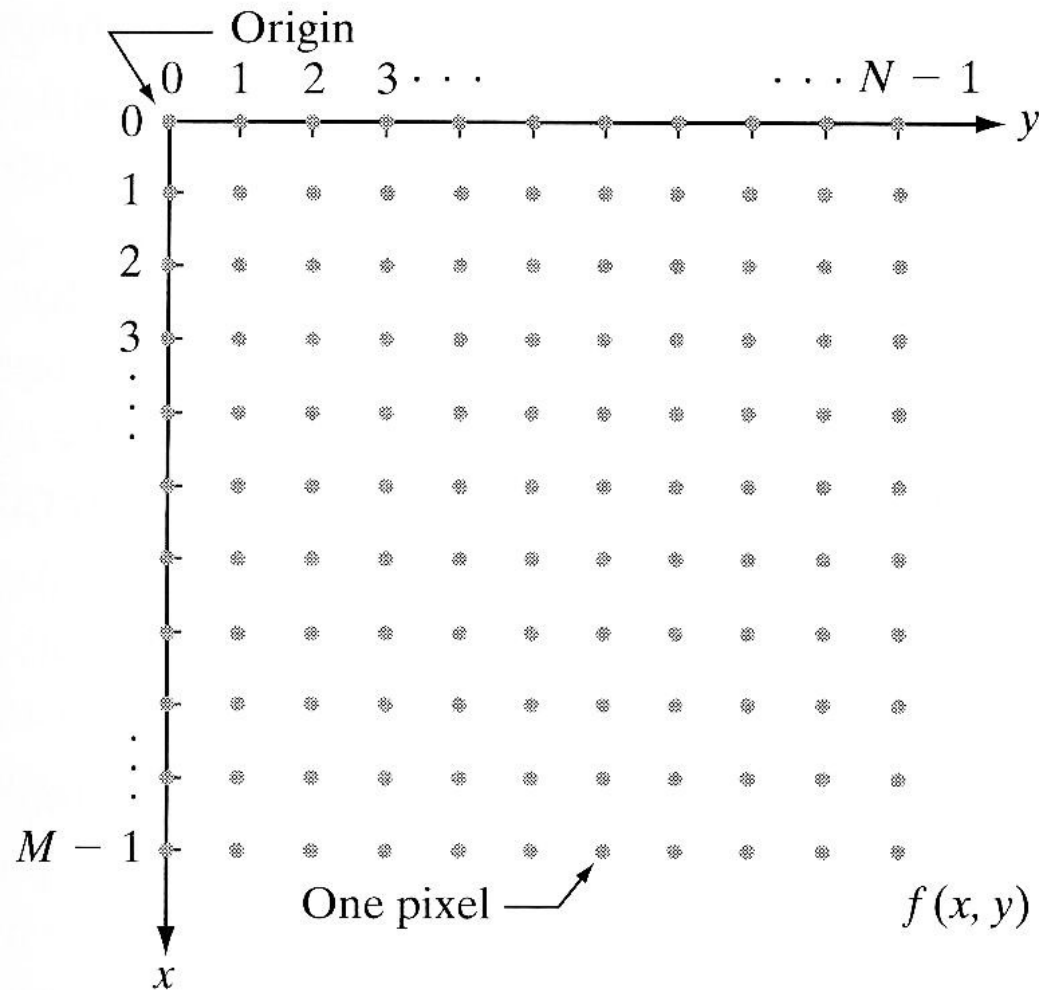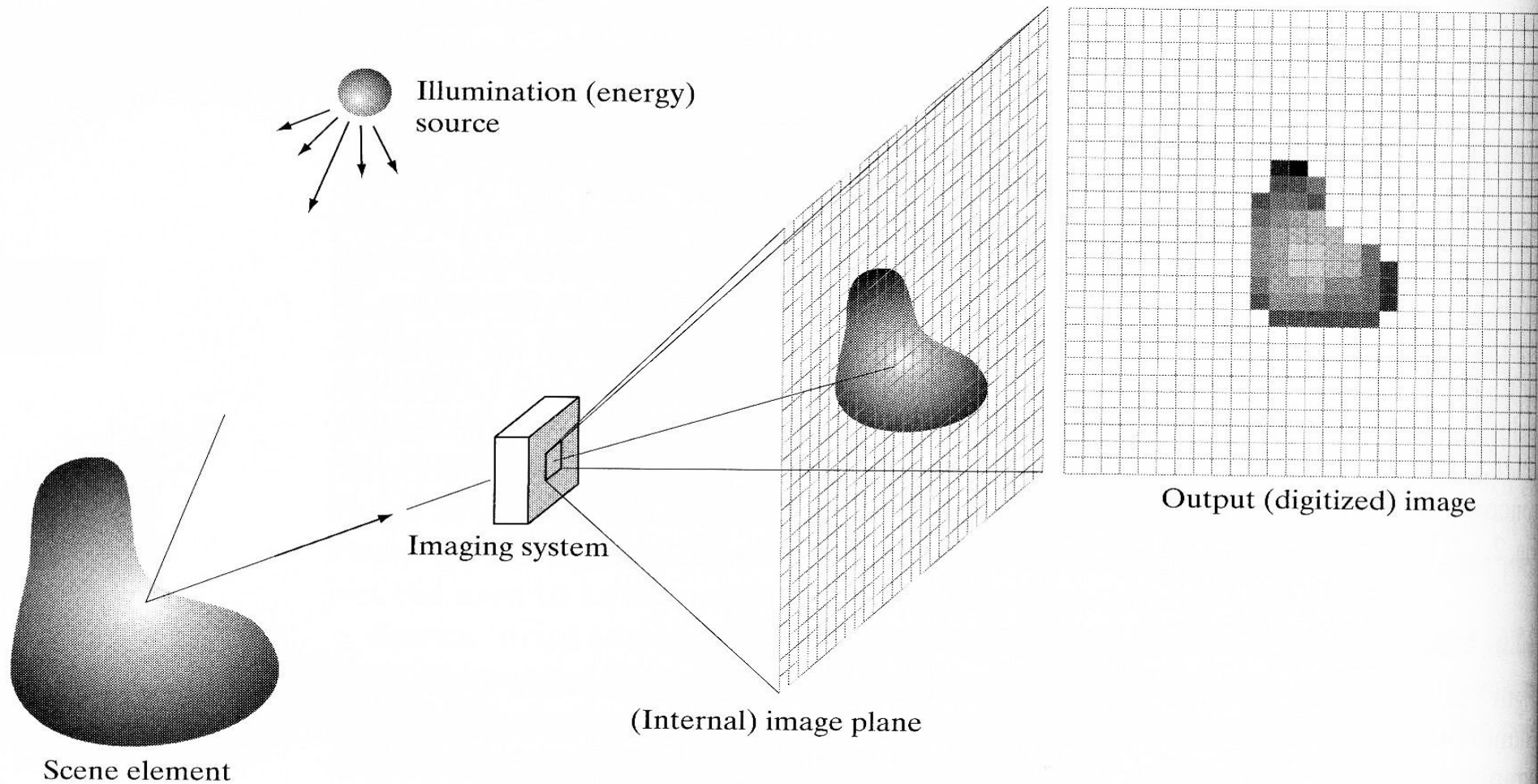
One pixel

$f(x, y)$

x

FIGURE 2.18
Coordinate convention used in this book to represent digital images.

many other books/papers, x-axis is in the horizontal direction

2-D Sampling (Spatial Domain)

Illumination (energy)
source

Imaging system

(Internal) image plane

Output (digitized) image

Scene element

a
b c d e

FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.
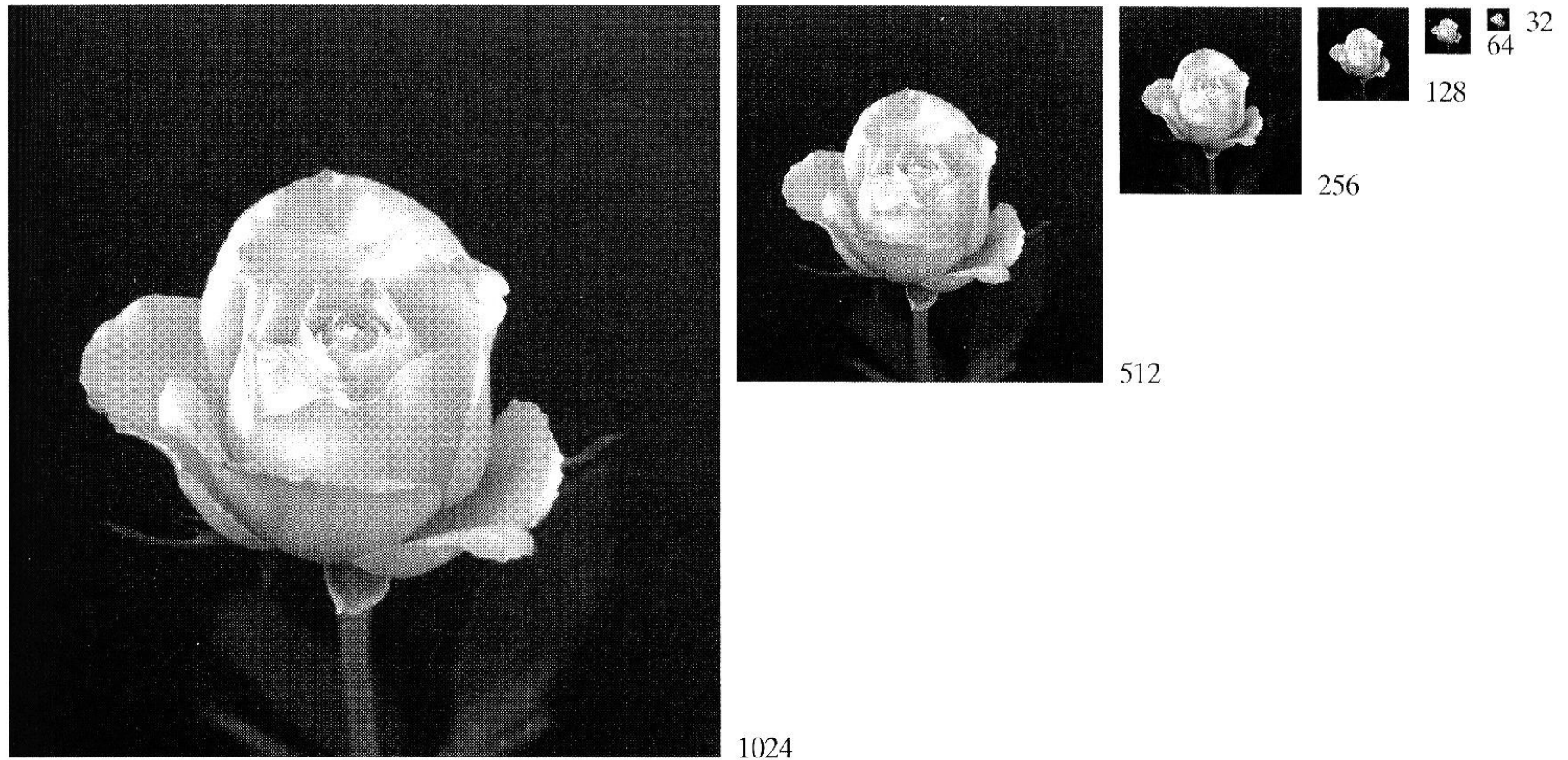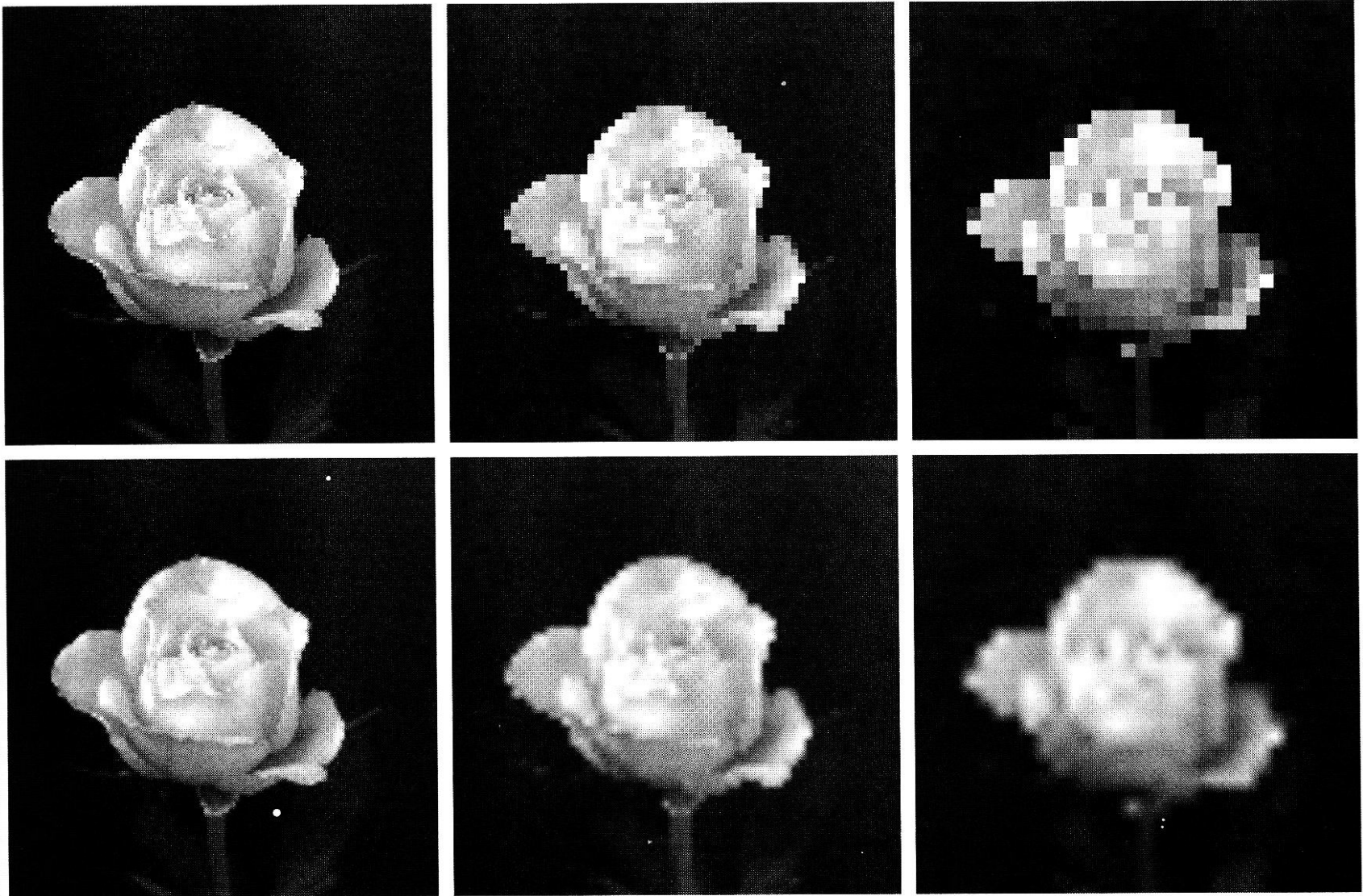
Resolution

FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

a b c
d e f

FIGURE 2.25 Top row: images zoomed from 128 × 128, 64 × 64, and 32 × 32 pixels to 1024 × 1024 pixels, using nearest neighbor gray-level interpolation. Bottom row: same sequence, but using bilinear interpolation.
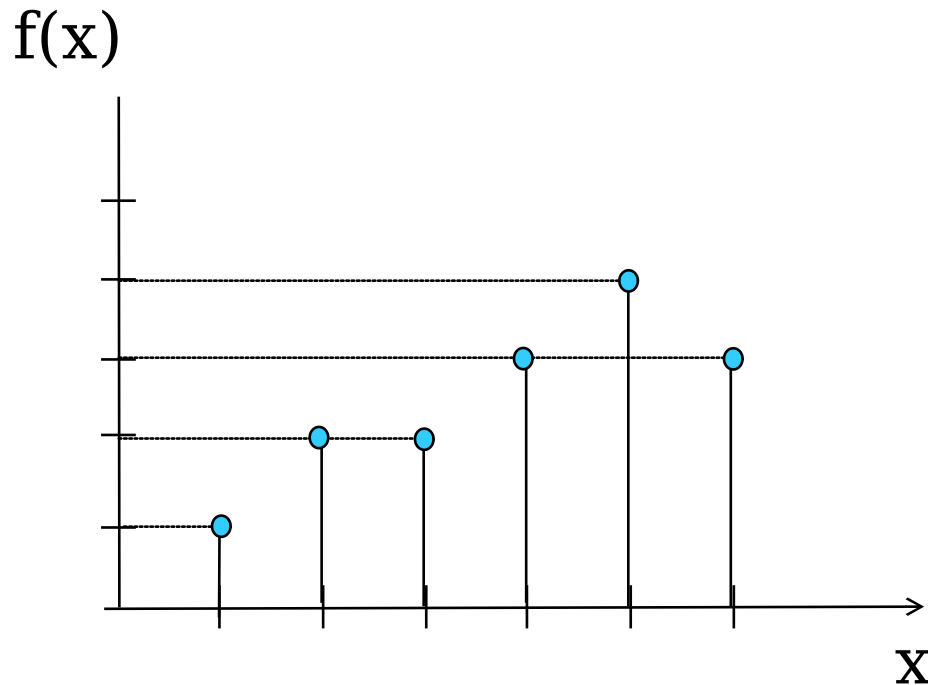
Resolution (in dpi)

a b
c d

FIGURE 2.20 Typical effects of reducing spatial resolution. Images shown at: (a) 1250 dpi, (b) 300 dpi, (c) 150 dpi, and (d) 72 dpi. The thin black borders were added for clarity. They are not part of the data.
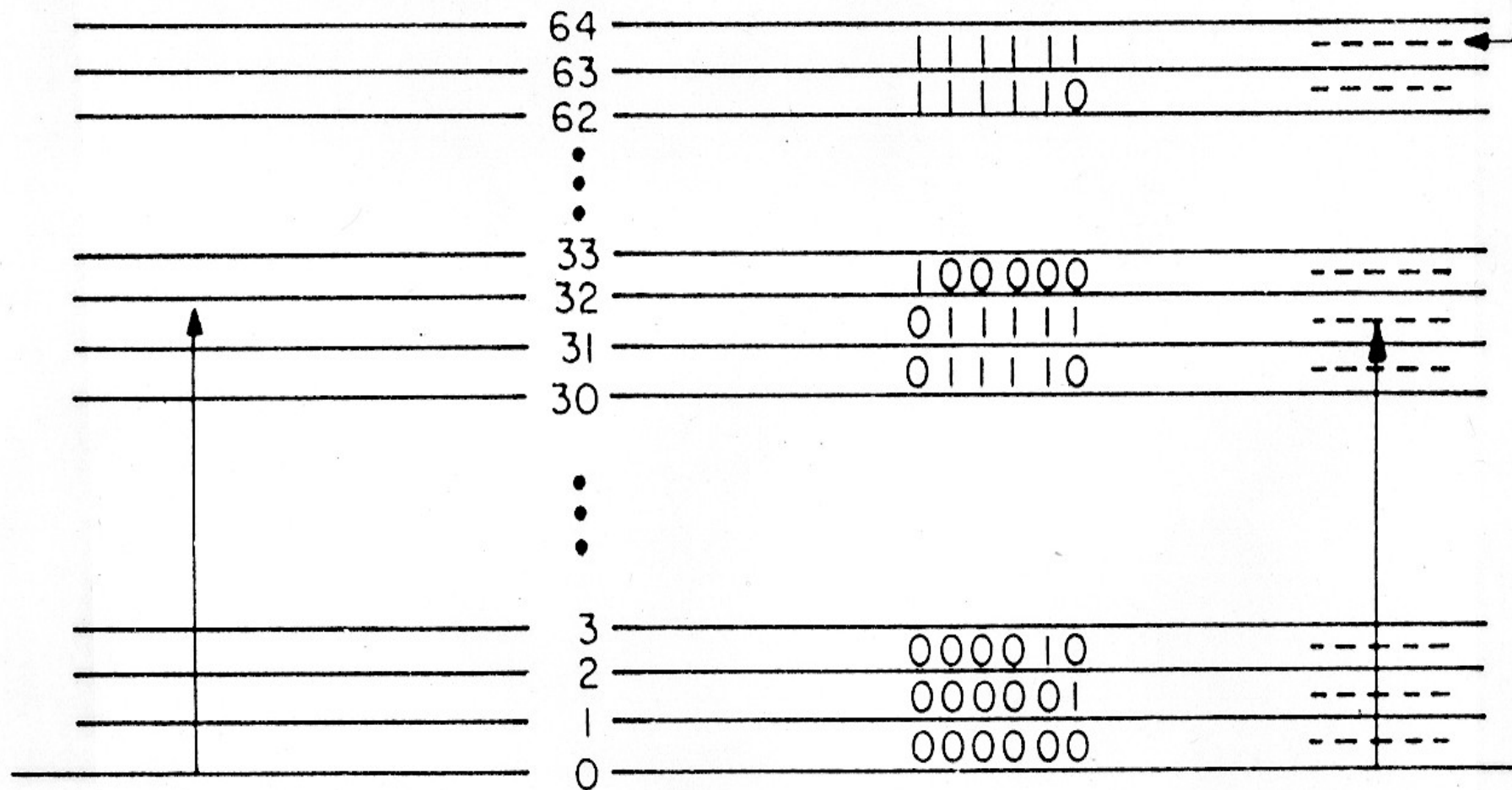
Quantization

f(x)

x

✂ Review binary number system:
Conversions between binary and decimal number systems

Example of Quantization

Continuous

Discrete

RECONSTRUCTION LEVELS

64								- - - - -
63						0	- - - -
62						
•		
•		
•		
33		
32	1 0 0 0 0 0	- - - - -
31	0 1 1 1 1 1	- - - -
30	0 1 1 1 1 0	- - - -
•		
•		
•		
3		
2	0 0 0 0 1 0	- - - - -
1	0 0 0 0 0 1	- - - - -
0	0 0 0 0 0 0	- - - - -

ORIGINAL
SAMPLE

QUANTIZATION
DECISION
LEVELS

DIGITAL
CODE

QUANTIZED
SAMPLE

Quantization

Example:

S: 0 1 2 3 4 5 6 7 (3 bits)

Quantization:
Quantization step-size Q=2:   S/2, truncate
Quantization Levels (Q_l):   0 0 1 1 2 2 3 3 (2 bits)
Inverse quantization (x2):   0 0 2 2 4 4 6 6
Quantization error   :   0 1 0 1 0 1 0 1
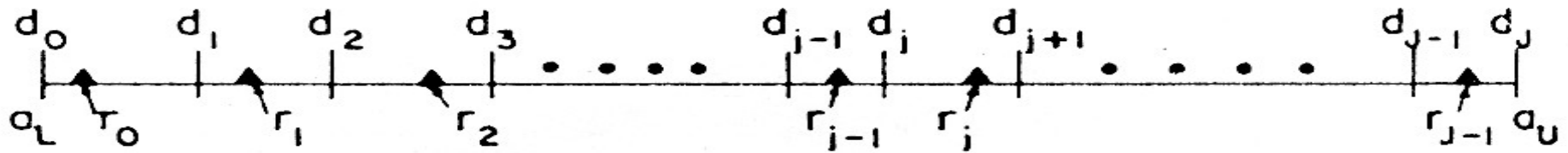
Quantization step-size Q=4:   S/4, truncate
Quantization Levels (Q_l):   0 0 0 0 1 1 1 1   (1 bit)
Inverse Quantization (x4):   0 0 0 0 4 4 4 4
Quantization error   :   0 1 2 3 0 1 2 3

Quantization Levels

DECISION LEVELS

d_0 $\quad d_1 \quad\quad d_2 \quad\quad d_3 \quad\quad\quad\quad\quad d_{j-1}\ d_j \quad\quad d_{j+1} \quad\quad\quad\quad\quad d_{J-1}\ d_J$

$a_L \quad r_0 \quad\quad r_1 \quad\quad\quad r_2 \quad\quad\quad\quad\quad r_{j-1} \quad r_j \quad\quad\quad\quad\quad\quad\quad r_{J-1}\ a_U$
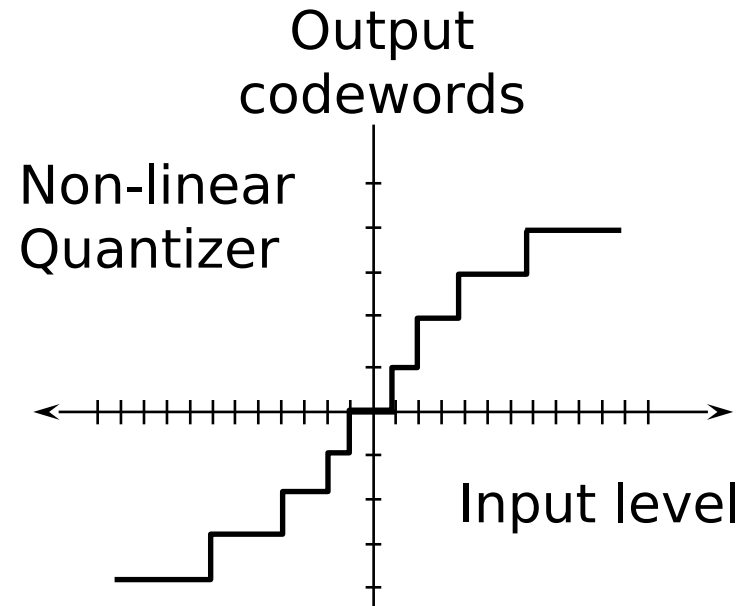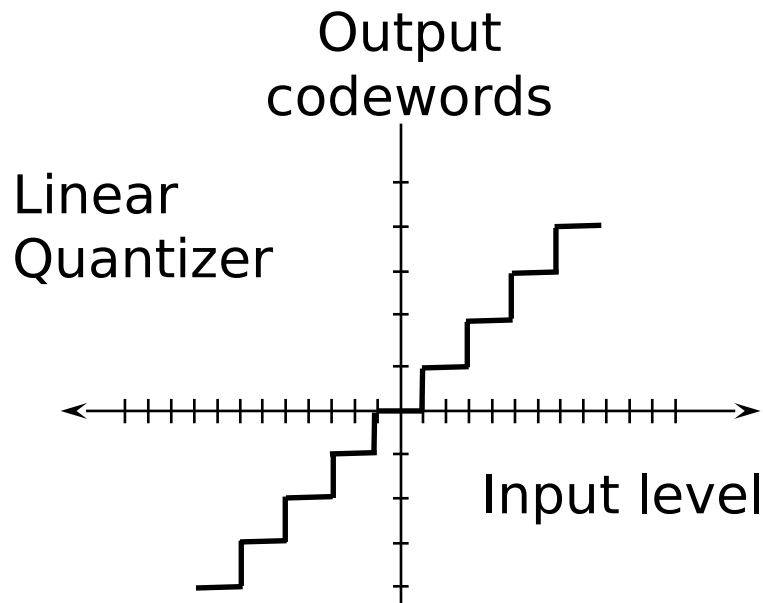
RECONSTRUCTION LEVELS

(a) LINE REPRESENTATION

RECONSTRUCTION LEVEL

OUTPUT

DECISION LEVEL

INPUT
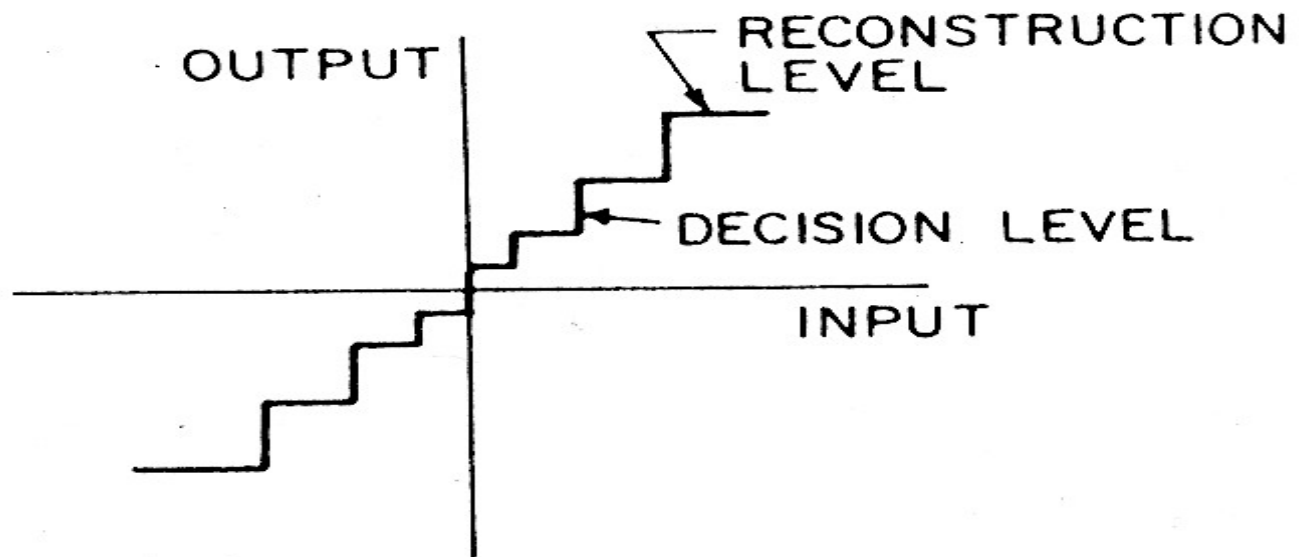
(b) STAIRCASE REPRESENTATION

Quantization

- Many to one mapping that reduces the number of possible signal
  values at the cost of introducing distortions
- Many different ways of implementation (table lookup, divide by the
  quantization step-size and round/truncate)
- Often act as a "control knob" for trading off image quality
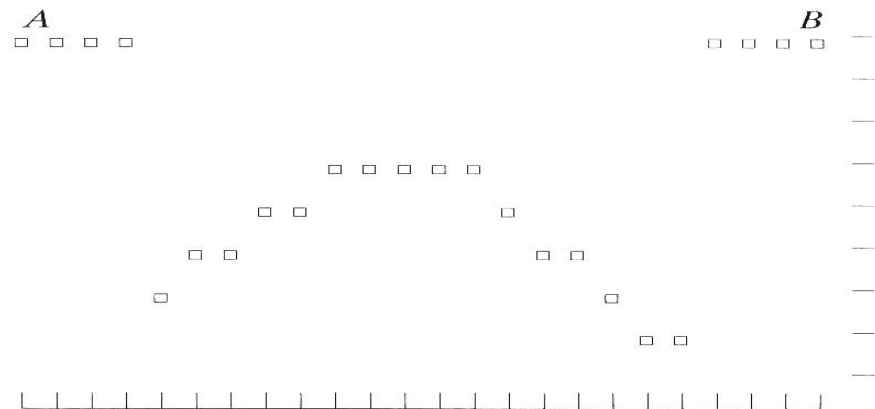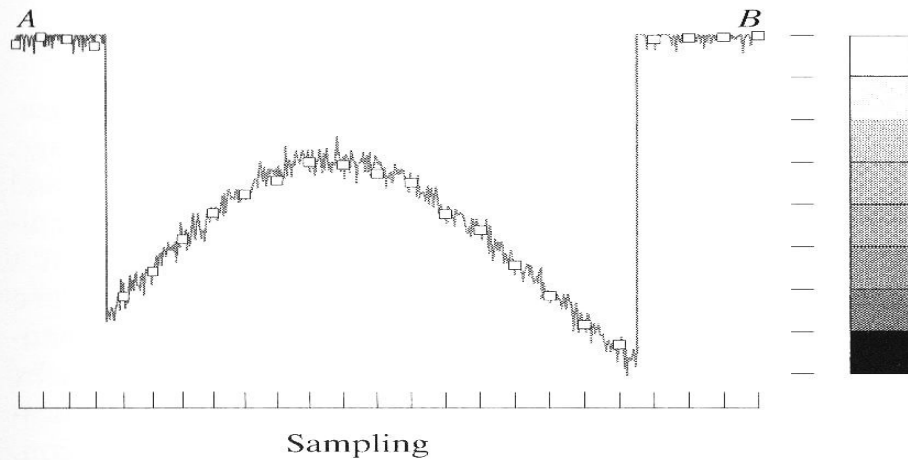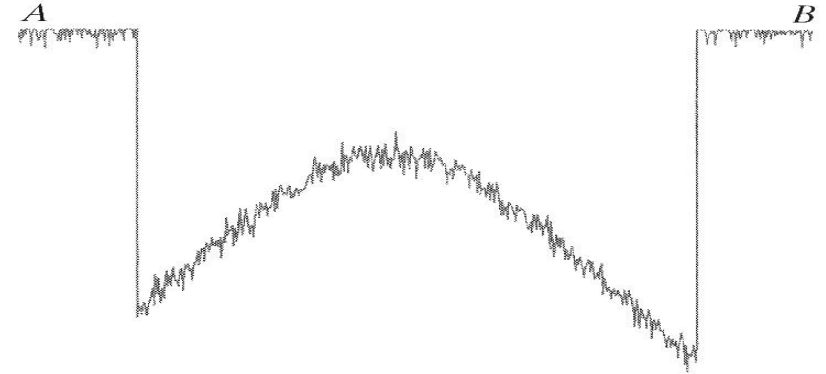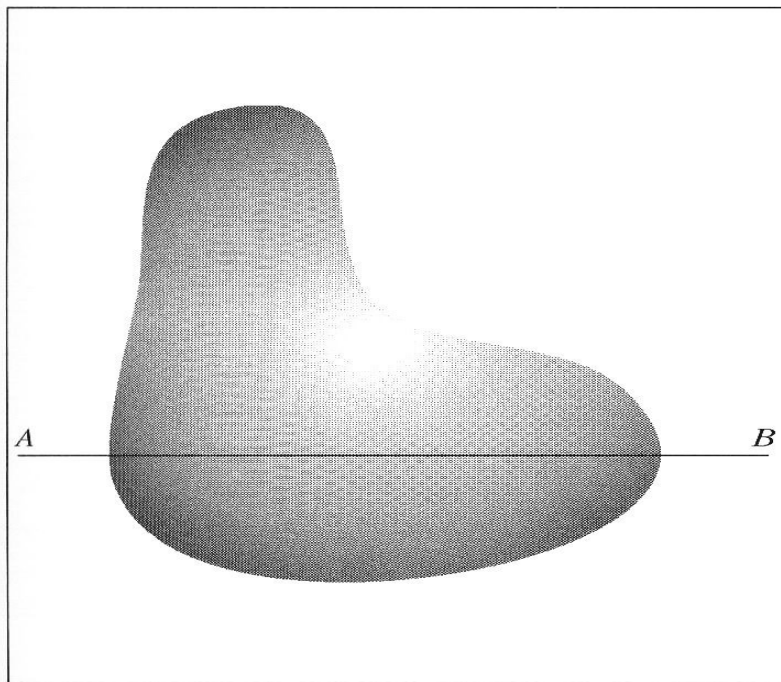
a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.
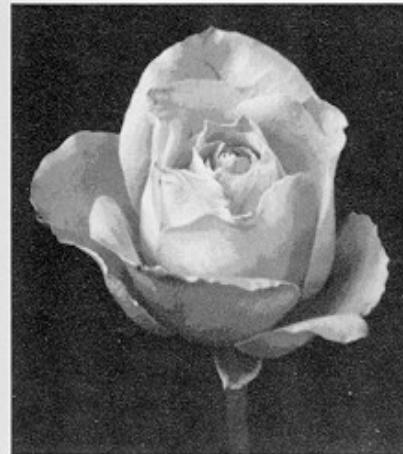
128,
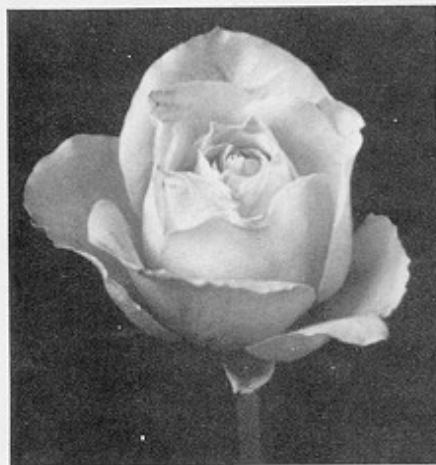64, 32, 16, 8, 4, 2 (1-bit)
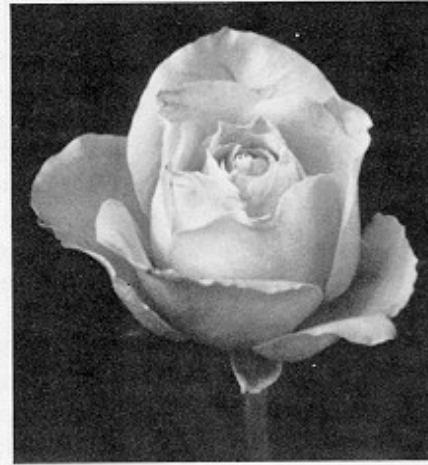levels

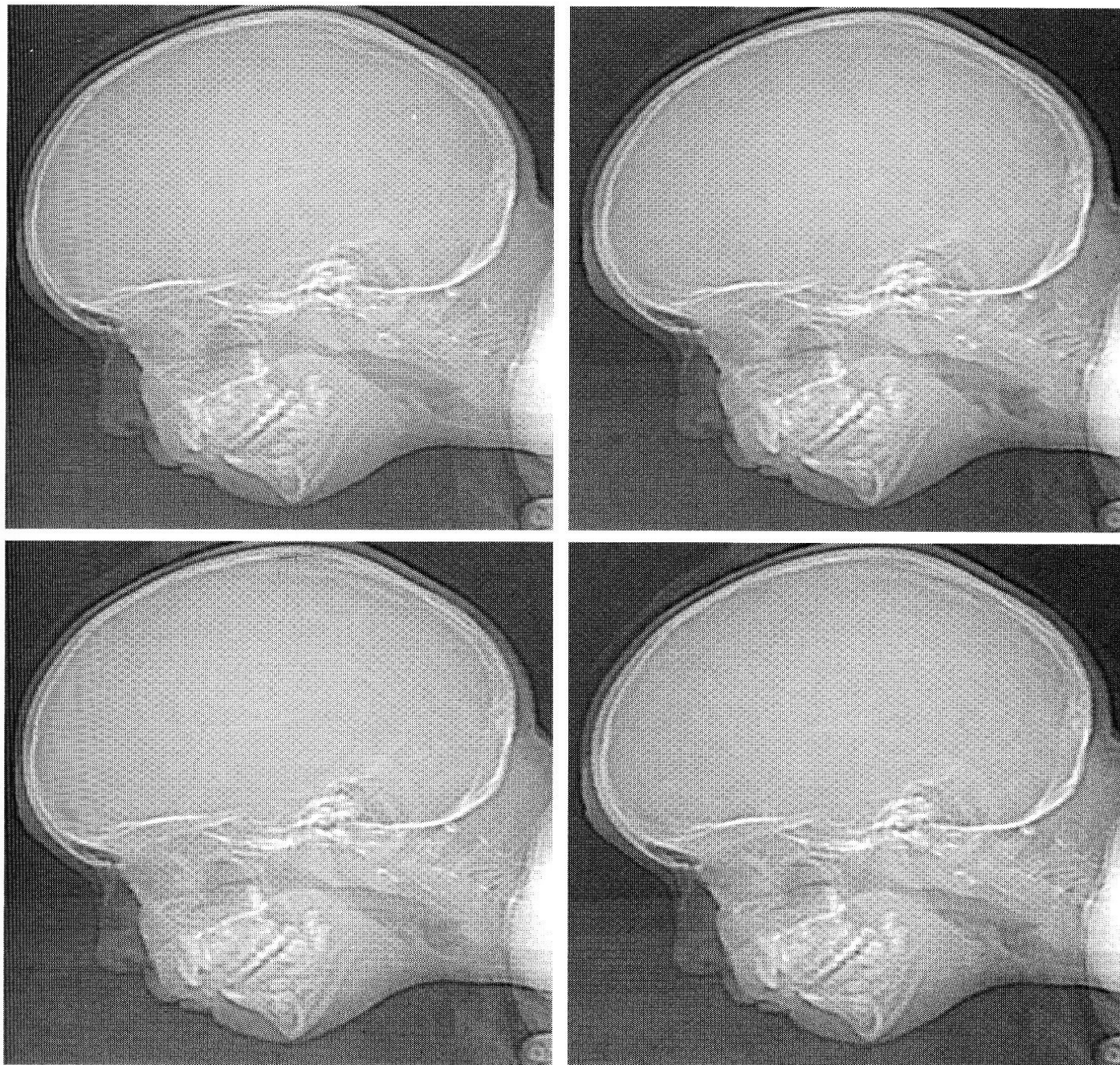(a)   (b)   (e)   (f)
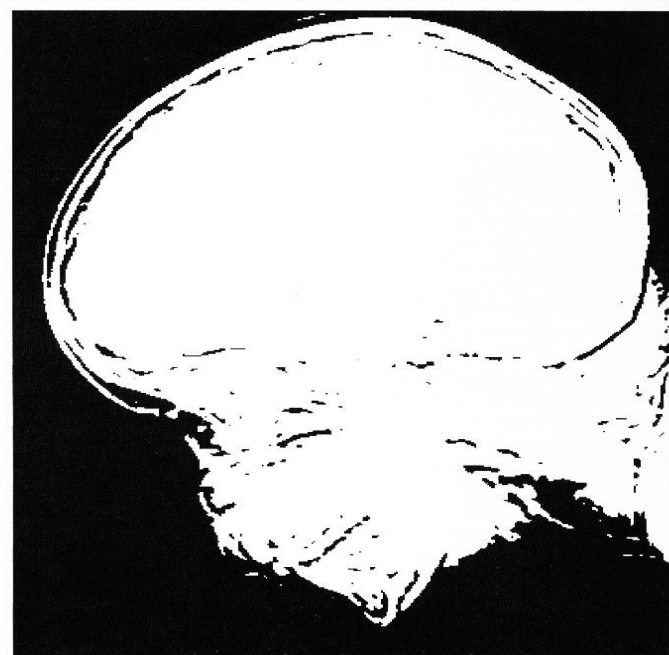
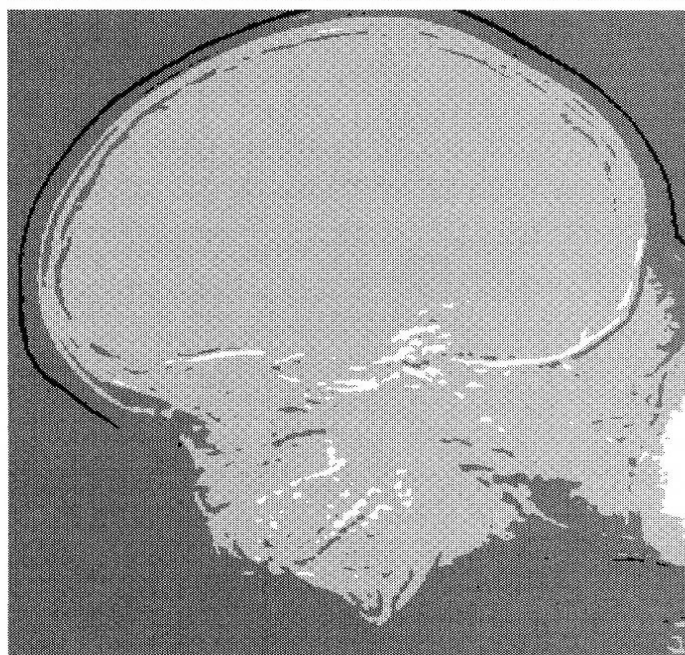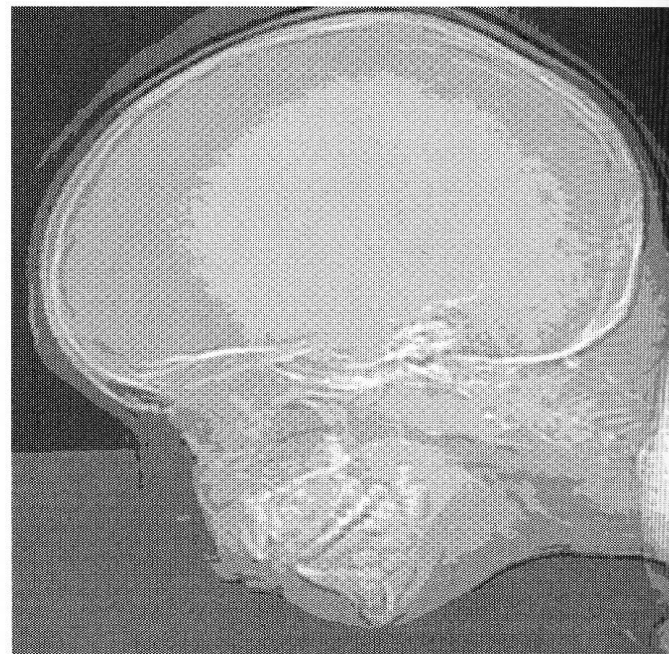(c)   (d)   (g)   (h)

FIGURE 2.21
(a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

FIGURE 2.21
(Continued)
(e)–(h) Image
displayed in 16, 8,
4, and 2 gray
levels. (Original
courtesy of
Dr. David
R. Pickens,
Department of
Radiology &
Radiological
Sciences,
Vanderbilt
University
Medical Center.)
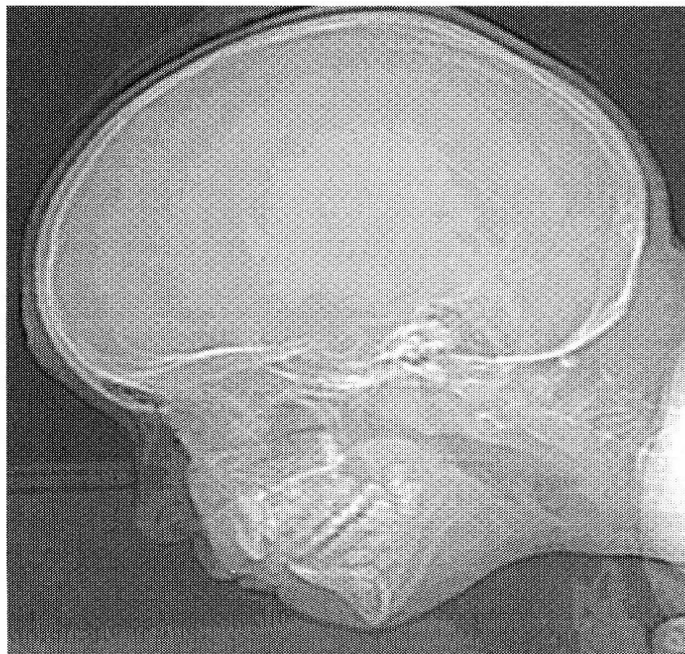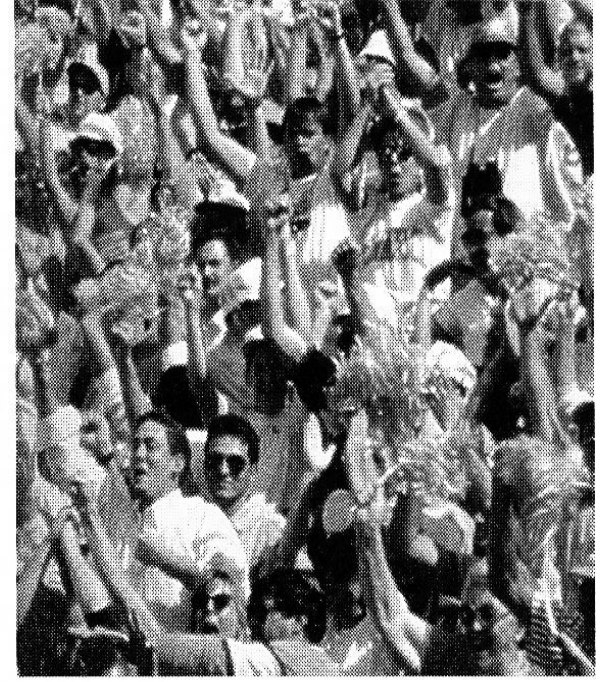
a b c

FIGURE 2.22 (a) Image with a low level of detail. (b) Image with a medium level of detail. (c) Image with a relatively large amount of detail. (Image (b) courtesy of the Massachusetts Institute of Technology.)

Resolution vs. Quantization Levels

FIGURE 2.23
Representative
isopreference
curves for the
three types of
images in
Fig. 2.22.

NxN pixels
k bits/pixel
kN² bits/picture

✂ Isopreference curves tend
to
become more vertical as
the
detail in the image
increases:
-> images with a large
amount
of detail, only a few gray
levels
may be needed
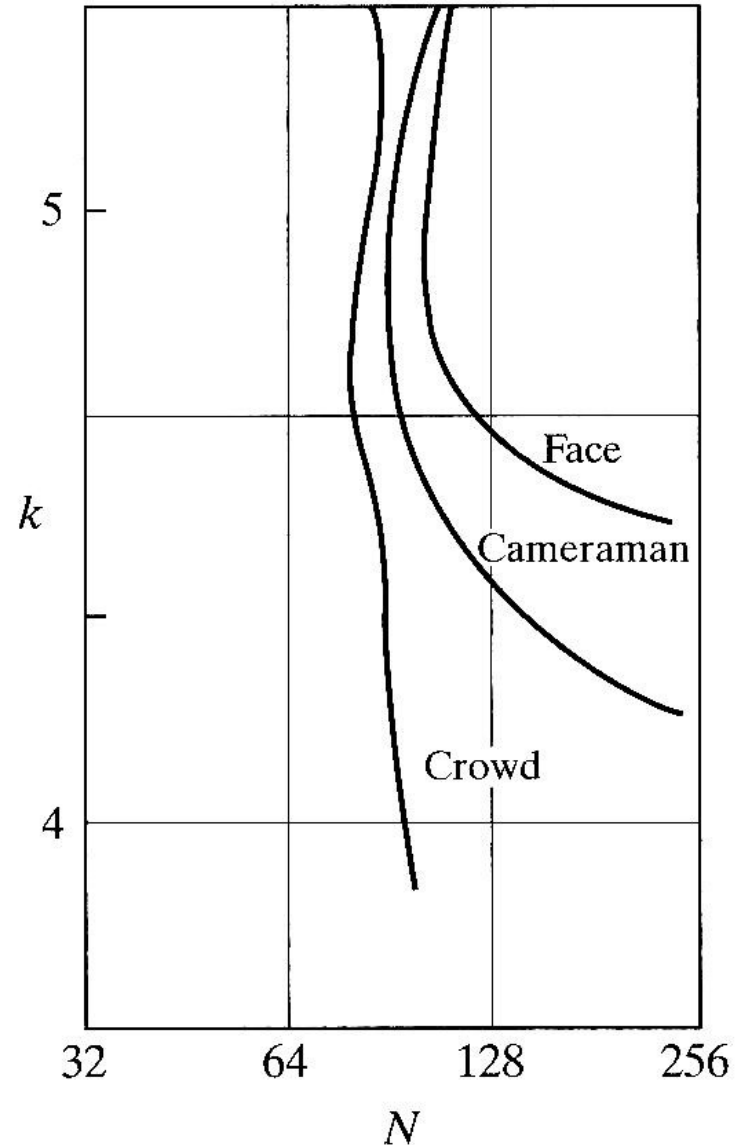
Image Data

- **Binary:** 0 & 1 (1 bit/pixel, mainly line-drawing or
   documents)

- **Gray Scale**: 0 (black), shades of gray,
  2^m - 1 (white). Typically m=8 (256
  quantization levels)

- **Color:** three primary color components,
  e.g. Red (R),
   Green (G), Blue (B).

- **Resolution:** 1024x1024, 512x512,
  256x256, 352x240, ...

Display and Printing with Halftoning

Halftoning: The use of bi-level pixels or dots to create the appearance of shades of gray by grouping the pixels in patterns to produce the desired shades for printing.

Different patterns may be used

Dithering

- Printers of modest dots per inch (dpi) have difficulty producing halftone cells that are small and still represent many gray levels; visually distracting patterns appear if regular patterns of dots are used.

- **Simple random dither**: for each possible position (where the printer can place a black dot), a random number is generated; if the number is below the gray scale value for that point, then the dot is printed.

Dithering

Common Image Formats

- BMP (Bitmap), GIF (Graphics Interchange Format), TIFF (Tagged Image Format File), JPEG (Joint photographic Expert Group), …

- Different formats contain different header information and descriptors, and use different data representations and compression methods.

Image Processing

- Enhancement
- Restoration
- Interpolation
- Compression
- Object segmentation and recognition
- Content-based indexing/retrieval
- ...

YIQ, YUV, YCbCr

- Luminance (Y) and two Chrominance components.

- **Goal**: for transmission efficiency and for maintaining compatibility with monochrome TV standard.

- The human visual system has greater sensitivity to changes in luminance than to changes in hue or saturation. YIQ calls for more bandwidth in representing Y, and less for I and Q. Useful for

YUV, YIQ, YCbCr

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$Y = 0.299(R-G) + G + 0.114(B-G)$$
$$C_b = 0.564(B-Y) \quad \text{and} \quad C_r = 0.713(R-Y)$$

$$\begin{bmatrix} Y \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.169 & -0.331 & 0.500 \\ 0.500 & -0.419 & -0.081 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 1.4021 \\ 1.0 & -0.3441 & -0.7142 \\ 1.0 & 1.7718 & 0.0 \end{bmatrix} \begin{bmatrix} Y \\ C_b \\ C_r \end{bmatrix}$$

UV is used in European TV broadcasts,
IQ is used in U.S. TV broadcasts. YCbCr used in video codin

$U=0.492(B-Y),\ V=0.877(R-Y)$
C_b and C_r are scaled and offset versions of U and V.

Human Color Perception (HSI/HSV)

- Human described a perceived color in terms of: **Hue, Saturation, and Intensity (Value)**.

- **Hue:** a subjective measure of color using conventional nomenclature: such as "red", "yellow", or "purple". Normal eye can distinguish among 200 hues. Colors that contain a hue component are called "chromatic colors," otherwise called achromatic

HSI/HSV Color Systems (cont.)

- **Saturation:** relative purity or the amount of "white" light mixed with a hue. For example, Pink (50% Saturation) has the same perceived hue (red), but is a whiter red. Lavender is a whiter violet.

- **Intensity (Value):** indicates the perception of brightness or darkness.

HSI/HSV Color Systems (cont.)

- **Hue, Saturation, and Intensity/Value** (HSI/HSV) are the three main characteristics of human perception to colors, therefore they offer ideal models for image processing systems.

- Some usefulness of HSI/HSV models: design of imaging systems for automatically determining the ripeness of fruits and vegetables, or inspection of quality of finished color goods.

HSI Color Triangle & Color Solid

(a)

(b)

HSI Color System

✂ Hue is defined as the angle with respect to the red axis;
Saturation is represented by the closeness to the
pyramid surface; Intensity is denoted by the
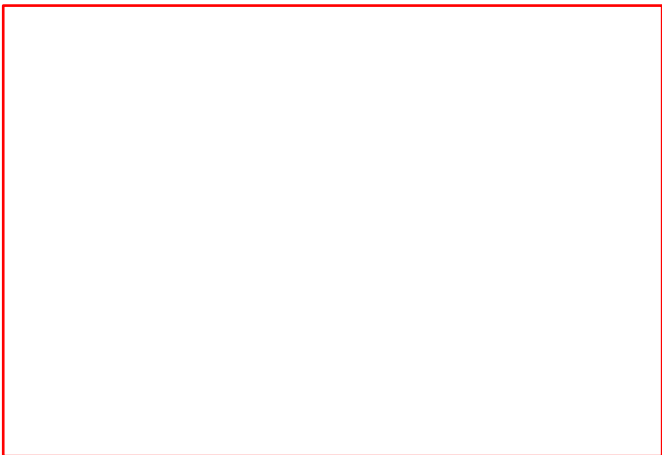perpendicular distance from the black point

✂ Red (0,240,120), Yellow (40,240,120), Green
(80,240,120), Cyan (120,240,120), Blue
(160,240,120)

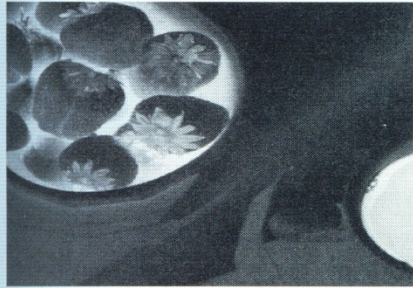# RGB to HSI

HSI to RGB

HSI to RGB (cont.)

HSV

- HSV is usually visualized as a cone
  - The bottom point of the cone is black
  - The top is a color wheel with white at the center and strong colors

A full-color image and its various color-space components
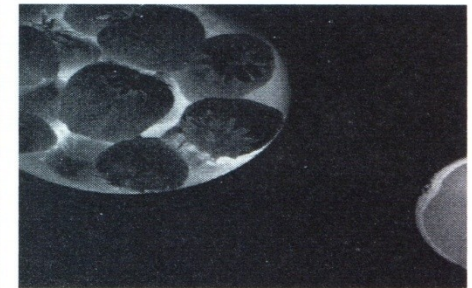

Full color

Cyan

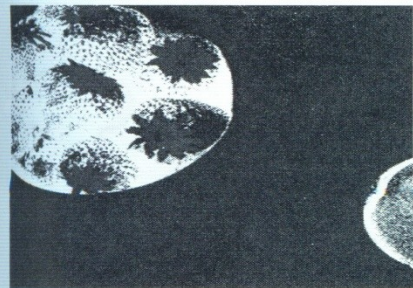Magenta

Yellow

Black

Red

Green

Blue

Hue

Saturation

Intensity

FIGURE 6.30 A full-color image and its various color-space components. (Original image courtesy of Med-Data Interactive.)

High saturation

Low saturation

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Brighter image

Darker image

High contrast

Low contrast

High resolution

Low resolution

A Tutorial of Python for Digital Image Processing

scipy H 、 W 、 C 的矩阵。

```python
import matplotlib.pyplot as plt
from scipy import misc
import scipy
I = misc.imread('./cc_1.png')
scipy.misc.imsave('./save1.png', I)
plt.imshow(I)
plt.show()
```

R G B components

- R=I(:,:,1);
- G=I(:,:,2);
- B=I(:,:,B);